Let’s Play with a Yagi

Exploring antennas and physics

Michelle Paquette October 14, 2022

PACIFICON™ 2022

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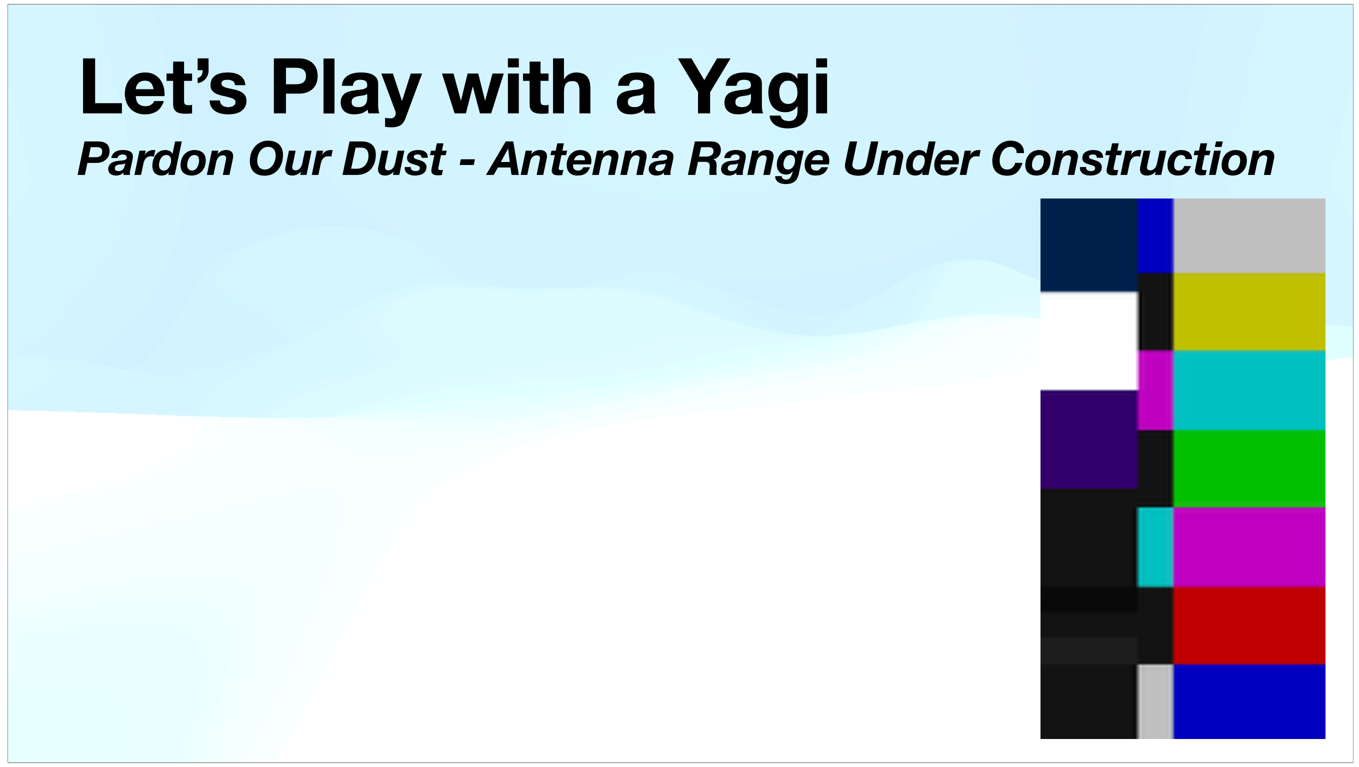

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Let’s Play with a Yagi

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Let’s Play with a Yagi

Exploring antennas and physics

- Review of physics behind antennas
  - Phase, Amplitude, Direction, and Location (PADL)
  - Aperture and power gain
- Dipoles and surroundings
- What if? …
- Parasitic elements
- What if? …
- The long and short of it

Review of physics behind antennas

1. $\nabla \cdot \mathbf{D} = \rho_v$
2. $\nabla \cdot \mathbf{B} = 0$
3. $\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$
4. $\nabla \times \mathbf{H} = \dfrac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$

It all starts with Maxwell's Equations

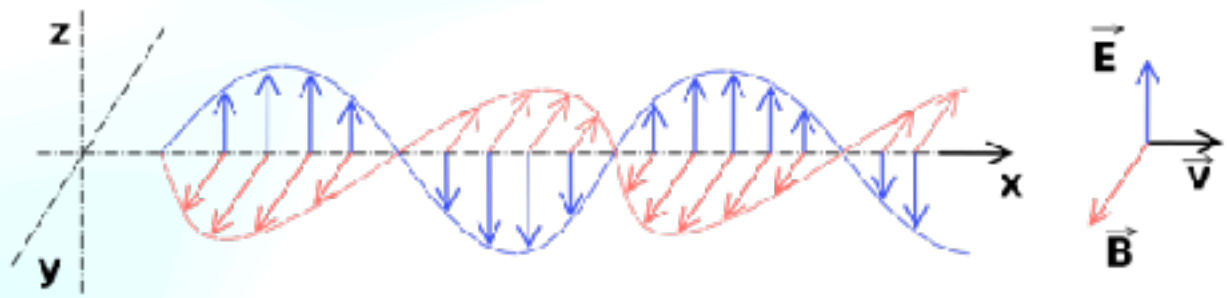
- 1 and 2 show Gauss's laws for the sum of electric and magnetic fields over a closed surface,
- 3 is Faraday's Law, and shows changing magnetic field gives rise to a changing electric field
- 4 is Ampere's law, and shows changing electric field gives rise to a changing magnetic field

1 shows the summation of an electric field over a closed surface, such as a sphere.
2 shows the closed sum, or integral, of a magnetic field over a closed surface is zero. Magnetic fields always present with two poles, and the field closed between them, so the summation of the fields should be zero.
3 and 4 show curl, or the way the fields wrap around a generator
3 is Faraday's Law, and shows the electric field curl is proportional to the rate of change of the magnetic field with respect to time. That is, a changing magnetic field gives rise to a changing electric field.
4 is Ampere's law, and shows magnetic field curl is proportional to the rate of change of the electric field with respect to time. That is, a changing electric field gives rise to a changing magnetic field.

Review of physics behind antennas

Maxwell's Equations

- A changing magnetic field gives rise to a changing electric field
- A changing electric field gives rise to a changing magnetic field
- This gives us a self-propagating set of fields!



So, if a changing electric field gives rise to a changing magnetic field, and a changing magnetic field gives rise to a changing electric field…

The electric and magnetic fields advance at the speed of light. The changing electric field produces a magnetic field. The changing magnetic field produces an electric field, a self-sustaining interaction.

Review of physics behind antennas

Radiation and interesting interactions

The meter is displaying received signal strength

Note how it changes as the antenna orientation and path varies.

Demo: Polarization, radiation pattern, and interaction with metallic objects

Show dipole vertical and in-plane

Rotate to end-on, point out dip in signal

Return to vertical in-plane, rotate polarization, point out

Attach antenna to board at zero point

Insert metal sheet into path. Diffraction effects let signal continue, a bit weaker

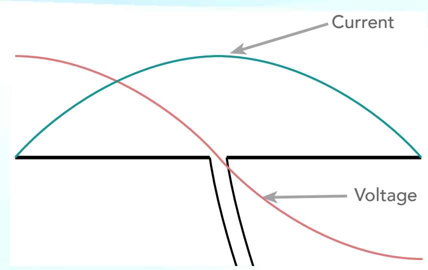
Place metal about 1 meter behind antenna.   Move towards antenna. What happens?

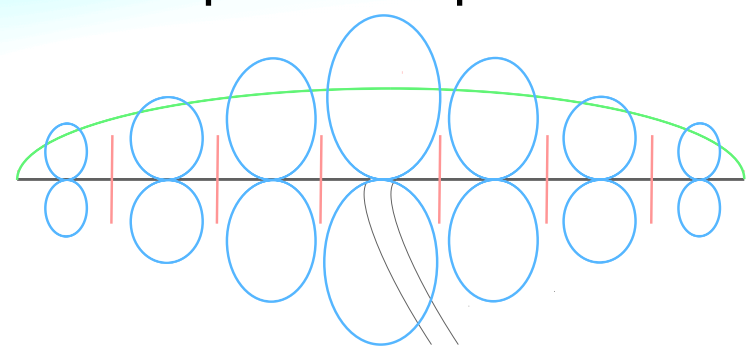
Phase, Amplitude, Direction, and Location (PADL)

Review of physics behind antennas

Phase, Amplitude, Direction, and Location

- **Phase describes where the current at a point is on the sine wave**
- **Amplitude describes instantaneous RF current at that point**
- **Direction is how the current flows, left or right for this dipole**
- **Location is just the position of the point in free space**



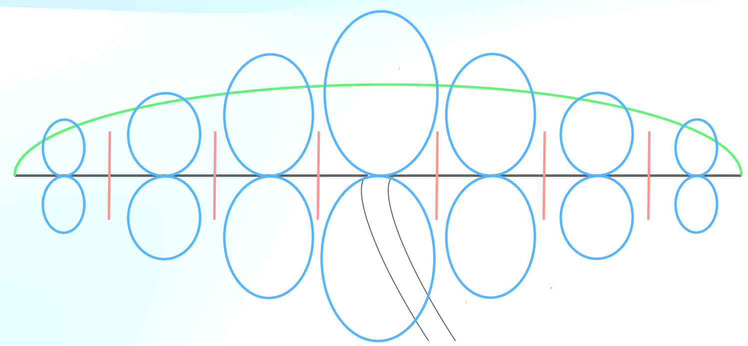


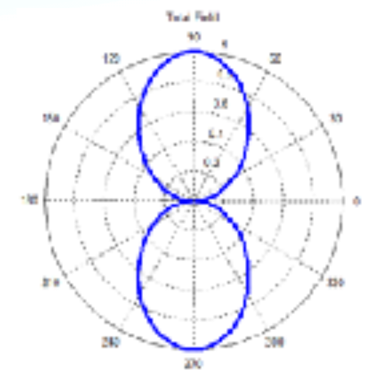
We can break a dipole or any antenna element into many short segments, approaching a point in size. Using PADL, Phase, Amplitude, Direction, and Location, we can determine the electromagnetic radiation from each of these points.

Review of physics behind antennas

Phase, Amplitude, Direction, and Location

Knowing the electromagnetic radiation at each infinitesimal segment, software like MATLAB or EZNEC can perform the integral calculus to sum these PADL terms to form the far field pattern.



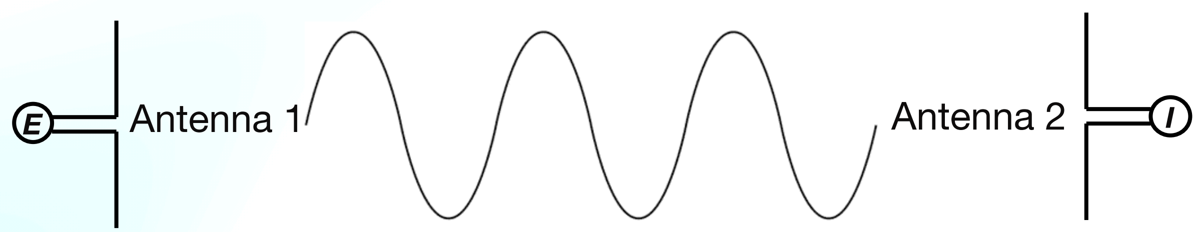


We can break a dipole or any antenna element into many short segments, approaching a point in size. Using PADL, Phase, Amplitude, Direction, and Location, we can determine the electromagnetic radiation from each of these points.

Review of physics behind antennas

Reciprocity

- **<u>Reciprocity</u> states that the receive and transmit properties of an antenna are identical**.
- **Antennas do not have distinct transmit and receive radiation patterns**



More formally, the ratio of transmitted power from the transmitting antenna to the received power of the receiving antenna will not change even when the modes of the antennas are interchanged. This is a case of what physicists call Lorentz reciprocity.

Hence, antennas do not have distinct transmit and receive radiation patterns - if we know the radiation pattern in the transmit mode then we also know the pattern in the receive mode.

I’m taking advantage of that in this presentation.

Review of physics behind antennas

Aperture and Gain

- **<u>Aperture</u> is, in a given direction for a polarization matched wave, the ratio of power available at the antenna terminals to the power flux density of a plane wave arriving from the given direction**
- **<u>Gain</u> is the ratio of the power received in a given direction to the power that would be received by an isotropic radiator (alternatively a dipole)**
- **Gain is proportional to aperture for a given wavelength. Aperture for a dipole or isotropic radiator is proportional to wavelength squared.**

Oof! For a really big antenna compared to the wavelength, aperture is proportional to physical size, like a big dish antenna. For antennas that are small compared to a wavelength, the aperture is not intuitively obvious.

Dipoles and surroundings

Mutual coupling

- **As two antenna elements are placed near each other, approaching the near fields of both, some power radiated by one element is received by the other, modifying the voltage and current value at the element to values representing the sum of fed and received power.**
- **This mutual coupling also modifies the impedance of the element, becoming what we call the *mutual impedance.***

Now that we have a bit of the basics out of the way, we can talk about some other effects that will become important when we move beyond dipole antennas.

Dipoles and surroundings

Metallic objects

The meter is displaying received signal strength

Note how it changes with the proximity of a metal surface

“You’ll recall that we saw something odd when we moved a metal sheet behind our antenna.”

Demo: Repeat interaction with metallic objects

Place metal sheet about 1 meter behind antenna.   Move towards antenna. What happens?

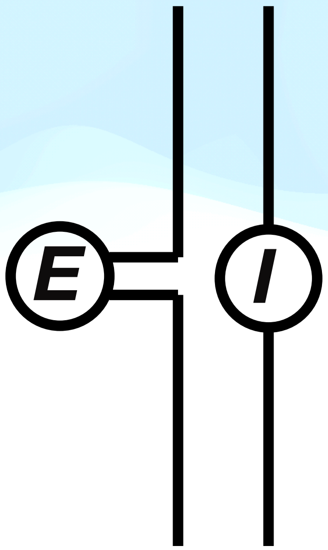
Mutual coupling produces RF current in sheet, which re-radiates.

PADL, Phase, Amplitude, Direction, and Location, drives interaction.

Dipoles and surroundings

Parasitic current

- ***Mutual coupling*** **induces a current flow in nearby conductors**
- **A second dipole, shorted in the center, will have a current induced in it. This current will be 180° out of phase with the first dipole**
- **The current in the second dipole will cause it to radiate as well**



Parasitic Elements

Parasitic 1/2 wavelength element interactions

The meter is displaying received signal strength

Note how it changes with movement of the other dipole element

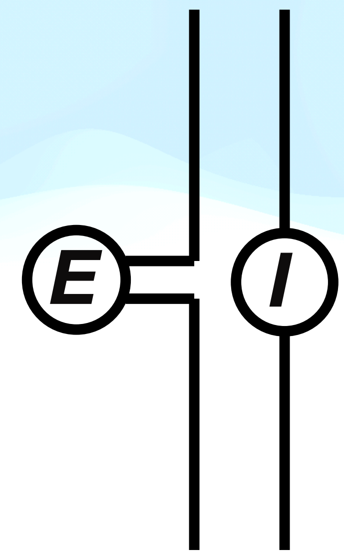
Demo: Repeat interaction with metallic objects

Move parasitic 1/2 ƛ element around driven element and observe changes

Parasitic Elements

Phase and location

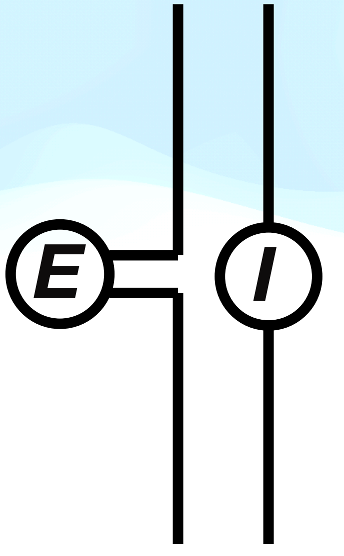
- *Mutual coupling* induces an electromotive force, a voltage, in nearby conductors
- A second dipole is shorted at the feedpoint. Transmission line theory says the short reflects the incident voltage 180º out of phase. The superposition produces a zero-voltage node at the feedpoint.
- For a resonant dipole the current will also be 180º out of phase
- The current in the second dipole will cause it to radiate as well



Parasitic Elements

Phase and location

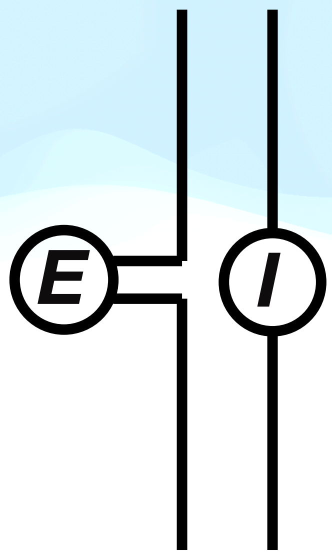
- **This shorted dipole in the near field of our dipole antenna element is called a parasitic element**
- **The current and it’s phase on the parasitic element is the negative value of the current incident upon it**
- **The amplitude and phase is determined by the complex coefficient of the mutual impedance *and the self-impedance of the parasitic element*.**



Parasitic Elements

Phase and location

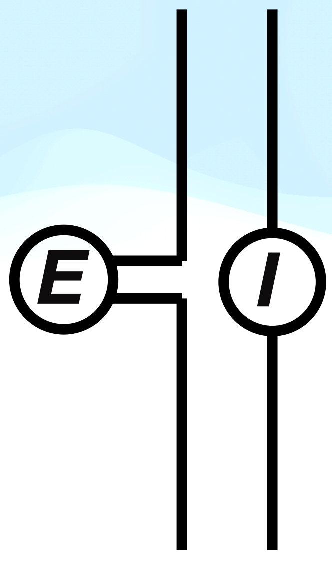
- **The *instantaneous* phase value of the parasitic element's current is also a function of the time (and thus phase difference) it takes the field to propagate from the driven element to the parasitic element.**



Parasitic Elements

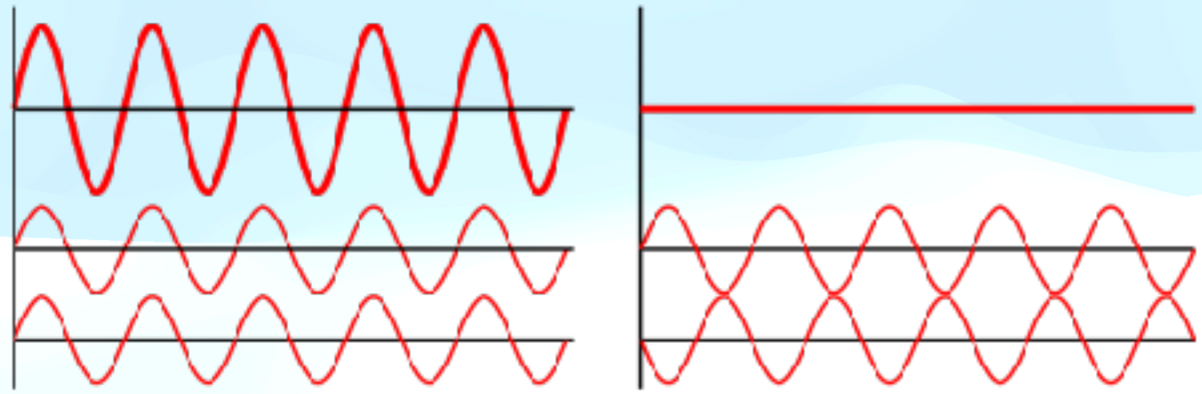
Phase and location

- Position - phase delay from propagation
- Mutual and self-impedance phase shift
- Phase reversal from mutual coupling
- We can alter position and self-impedance



Parasitic Elements

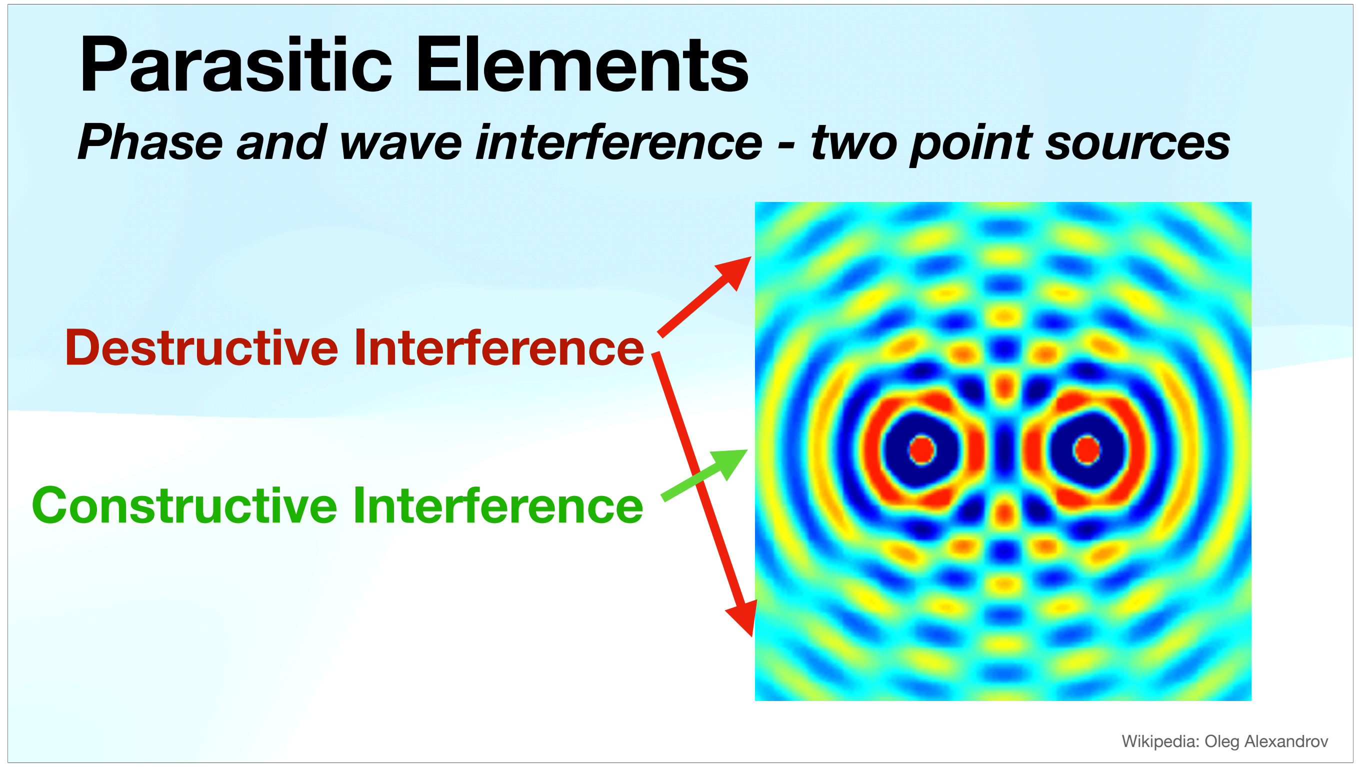
Phase and wave interference



Constructive Interference **Destructive Interference**

Wikipedia: original version: Haade; vectorization: Wjh31, Quibik

Here’s where that phase delay becomes important.
In one dimension first, where we can easily see the results



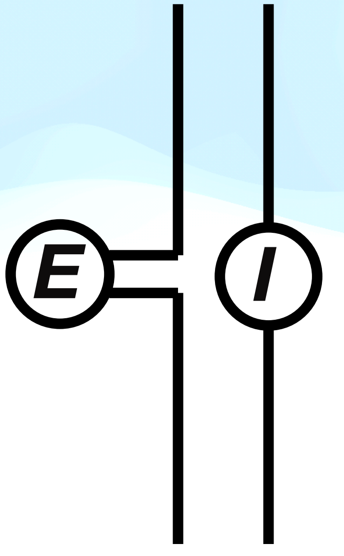
In two dimensions, the wavefronts rippling out from two point sources reinforce and cancel at different points relative to the two sources. Varying the spacing between the sources and the phase of the sources can shift the resulting pattern

We saw this effect from the relative positions for our antenna and other metallic objects, with constructive and destructive interference boosting or cancelling the signal from our test source.

Parasitic Elements

Phase and location

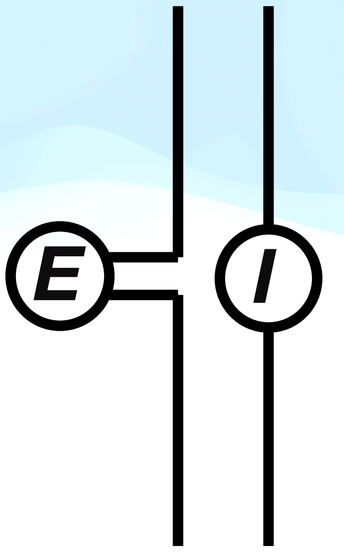
- We can alter position and self-impedance of our parasitic element to alter the phase relationship to the driven or receiving element
- The constructive and destructive interference patterns can be used to alter antenna radiation patterns.



Parasitic Elements

Phase and location

- **Making our parasitic element shorter than a half wavelength adds capacitive reactance to it's impedance, causing voltage to lag current.**
- **Making our parasitic element longer than a half wavelength adds inductive reactance to it's impedance, causing voltage to lead current.**
- **By making current lag or lead we can adjust the phase of the re-radiated signal**



Parasitic Elements

Parasitic reactive element interactions

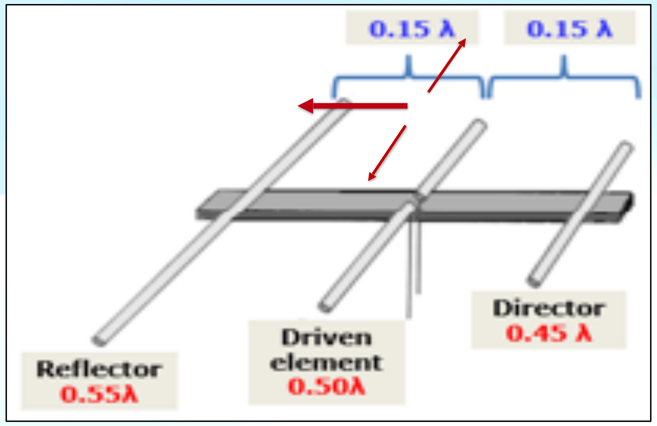
The meter is displaying received signal strength

Note how it changes with movement of the parasitic elements

Demo: Repeat interaction with metallic objects
Repeat 1/2 wave element demo around antenna.
Bring in shorter element, with leading current, and remove
Bring in longer element with lagging current. Place on board
Both parasitic elements! Bring in shorter element again, place on board
Mutual inductance alters tuning with new director, so re-adjust reflector element

Parasitic Elements

Controlled interference with phase and location



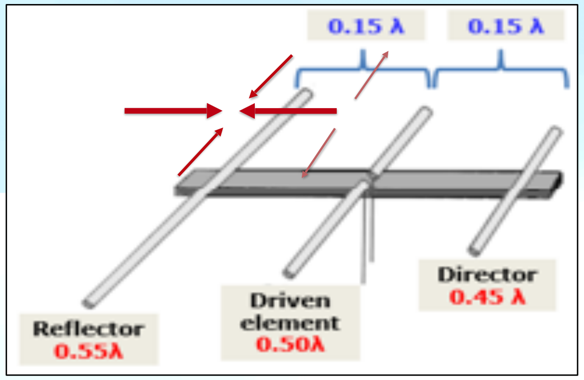
The original signal from the *Driven Element* travels to the reflector where it causes current to flow, re-radiating a signal.

We achieve this directionality by carefully controlling the way each element radiates a signal relative to other elements. The driven element is connected to the feed line, and the other, parasitic elements re-radiate the signal on the driven element.

There are signal delays from the travel time of a wave between elements, what we call a phase shift.

Parasitic Elements

Controlled interference with phase and location

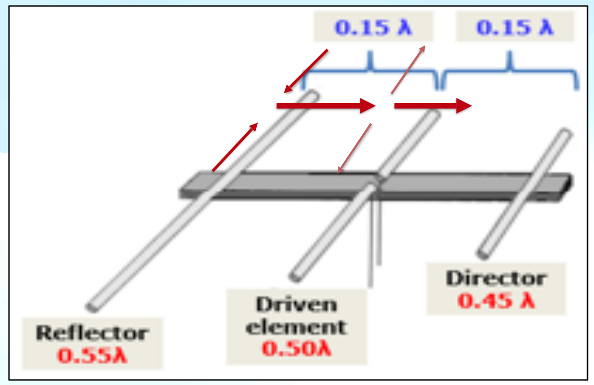


Re-radiated signals are 180° out of phase with the original signal, so that re-radiated and driven signals cancel in the direction of the reflector *(to the rear of the antenna)*

Each parasitic element also re-radiates the shifted signal arriving at it with a 180 degrees phase shift. This cancels out the driven elements signal in the direction of the reflector.

Parasitic Elements

Controlled interference with phase and location

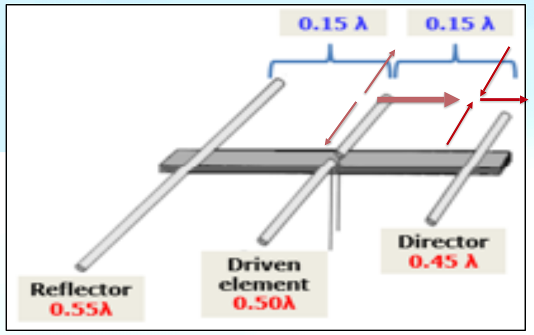


To the front of the antenna, the extra travel time for the radiated signal from the reflector causes it to reinforce the signal.

The reflector is a little longer than needed for our resonant frequency, making it inductive. This produces a lagging current flow, further shifting the phase of the re-radiated signal. When combined with the delay for the signal to traverse the 0.15 wavelength gap between the driven element and reflector, the re-radiated signal from the reflector is back in phase with the driven element signal in the forward direction, and so adds to it.

Parasitic Elements

Controlled interference with phase and location



A director element placed in front of the (*DE*) increases forward gain.

Additional reflectors make little difference in either gain or front to back ratio.

The director element also engages in this phase shifting dance, further reducing the signal moving backwards and adding to the forward signal.

Parasitic Elements

Adding a second director element

The meter is displaying received signal strength

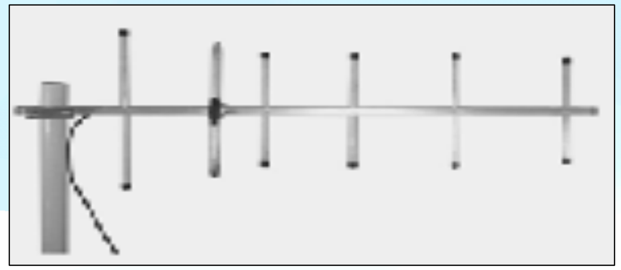
Note how it changes with a new element and off-axis measurements

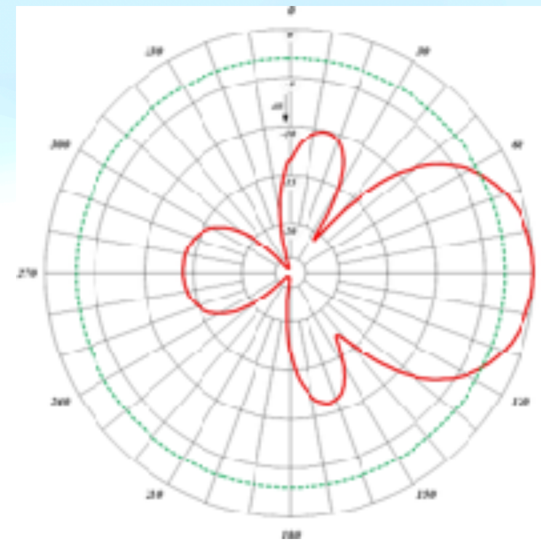
Demo: Add a second director
Show impact on off-axis signal

Compare to a commercial yagi for element spacing and placement

The Long and Short of It

Controlled interference with phase and location

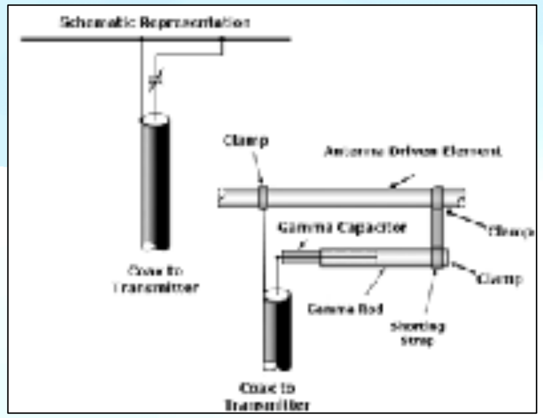




The constructive and destructive interference effects between the antenna's driven and parasitic elements result in a directional radiation pattern.

The Yagi antenna's parts, or elements, will generate radiation patterns that result in a very directional pattern for the antenna. The power radiated or received off the back of the antenna is a fraction of the amount in the forward direction.

The Long and Short of It
Feedpoint Impedance

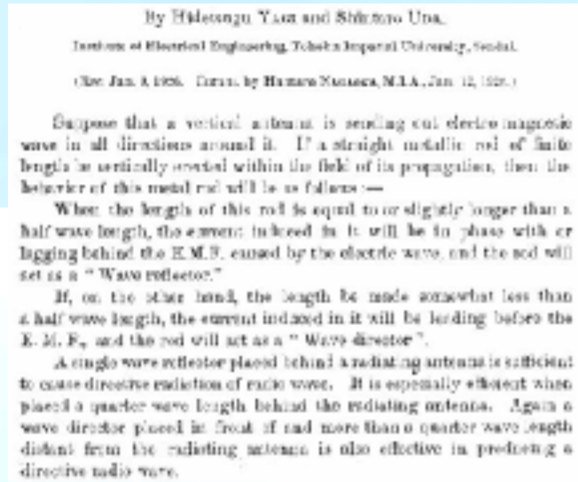


The mutual impedance of all these elements results in a feed point impedance that is often fairly low. A matching network or a folded dipole driven element compensate for this.

The gamma match is very popular for unbalanced feed systems, relying on the zero-voltage node at the center of each element. A balanced feed equivalent would be the T-match.

The Long and Short of It

Professors Yagi and Uda, Tohoku University, 1926



By Hidetsugu Yagi and Shintaro Uda.

Institute of Electrical Engineering, Tohoku Imperial University, Sendai.

(Rec. Jan. 8, 1926. Comm. by Hantaro Nagaoka, M.I.A., Jan. 12, 1926.)

Suppose that a vertical antenna is sending out electro magnetic wave in all directions around it. If a straight metallic rod of finite length be vertically erected within the field of its propagation, then the behavior of this metal rod will be as follows:—

When the length of this rod is equal to or slightly longer than a half wave length, the current induced in it will be in phase with or lagging behind the E.M.F. caused by the electric wave, and the rod will act as a "Wave reflector."

If, on the other hand, the length be made somewhat less than a half wave length, the current induced in it will be leading before the E. M. F., and the rod will act as a "Wave director".

A single wave reflector placed behind a radiating antenna is sufficient to cause directive radiation of radio wave. It is especially efficient when placed a quarter wave length behind the radiating antenna. Again a wave director placed in front of and more than a quarter wave length distant from the radiating antenna is also effective in producing a directive radio wave.

Professor Yagi wrote several English-language papers to introduce a new antenna design from his colleague Shintaro Uda to the world. Patent applications were filed in Japan and the USA, and US Patent US1860123A was granted in 1932 and assigned to RCA.

Let’s Play with a Yogi

Questions and Answers

Thank You!

Plug antenna books…